ARMY RESEARCH LABORATORY

SMARTweave Sensors for Assessing Ballistic Damage: a Feasibility Study

by Daniel J. Snoha, William O. Ballata, and Shawn M. Walsh

ARL-TR-1674 May 1998

Approved for public release; distribution is unlimited.

Army Research Laboratory
Aberdeen Proving Ground, Maryland 21005-5069

ARL-TR-1674 **May 1998**

SMARTweave Sensors for Assessing Ballistic Damage: a Feasibility Study

Daniel J. Snoha, William O. Ballata, Shawn M. Walsh
Weapons and Materials Research Directorate, ARL

Abstract

SMARTweave technology, developed and patented by the U.S. Army Research Laboratory (ARL), has been applied to monitor resin flow and cure progress in composite laminate processing. It has since demonstrated the capacity of being a viable sensing mechanism in other critical applications. In this feasibility study, for example, SMARTweave sensors have successfully shown the potential for detecting ballistic-impact-induced damage in a composite laminate. A sensing grid of electrically conductive graphite fibers was embedded in the composite specimens during lay-up of the glass-fabric preforms. The results of electrical resistance measurements preformed before and after ballistic impact, with the difference indicating the detection of induced damage (delamination), are presented herein. For purposes of qualitative comparison, a traditional, ultrasonic, nondestructive, evaluation technique was also used to capture the effects of the induced damage. This research was conducted during the period that the Materials Division was in transition from ARL, Watertown, MA, to the Rodman Materials Research Laboratory, Aberdeen Proving Ground (APG), MD.

Acknowledgments

The authors' appreciation goes to Clarissa DuBois and Suhas Malghan of the University of Delaware (UDel) for their assistance in manufacturing the test specimens, to Tom Carlson at the Aberdeen Test Center (ATC) for doing the ballistic testing, and to Knut Kreiger (UDel) and Patrick Sincebaugh (U.S. Army Research Laboratory [ARL]) for performing the ultrasonic inspection and interpreting the results.

INTENTIONALLY LEFT BLANK.

Table of Contents

List of Figures

INTENTIONALLY LEFT BLANK.

1. Introduction

1.1 Background. Over the last decade, the U.S. Army has initiated a number of programs specifically dedicated to exploring the potential of polymer composites as primary structural elements in a variety of critical and noncritical applications. Polymer composites present a number of attractive features with, perhaps, the most important being the weight savings offered by substituting composites for more traditional structural materials, such as steel or aluminum. Indeed, the "lightening of the force" has been and remains a fundamental goal of the Army. Every pound shed from an Army materiel system increases its ease and effective deployment while reducing cost associated with intermittent transportation. The major concern with polymer composites is whether or not they can effectively preserve, if not fortify, the performance of the material and systems that they replace; increasingly, prevailing economic constraints impose limits on the cost of delivering such composite systems affordably.

Traditionally, the U.S. Air Force has been the leader in the development and application of polymer composites, but, until recently, these have largely been relatively thin, graphite, fiber-reinforced materials. Conversely, the Army has been interested in thick-section, glass-reinforced composites for use not only as structural members but also for providing an additional measure of ballistic integrity. The distinction between "thin" and "thick" is still a largely debated issue. Suffice it to say that general agreement has established that a thick composite is one with a thickness of greater than a half inch; though, often attached to this statement is the provision that the type of reinforcement employed will give variance to this definition. It is important to note, however, that thickness is only one component in determining both processing and structural performance parameters for a given composite system.

While weight savings is the primary goal, there are other concerns that drive the development of Army-specific composite material. For example, the polymer itself must exhibit some degree of flame retardance. Additionally, once ignited, the polymer should not discharge a lethal concentration of fumes. These concerns, in fact, have driven both resin formulation and selection for prototype

versions of the composite infantry fighting vehicle (CIFV) and the composite armored vehicle (CAV). This has prompted the notion of "coinjection" to achieve the desired exterior ballistic and structural properties while minimizing safety and health risks.

Delamination is the prevalent mode of failure in composites. However, the physics involved offer a unique and highly effective means for absorbing large amounts of energy delivered to a structure, which may occur during ballistic impact. The process of impact-induced delamination initiates when the "lamina" within the composite begin to peel away from each other due to the enormous shear force acting on the composite. Pulling each of these lamina apart involves breaking the adhesive bonds that exist between the matrix and the reinforcing medium. Furthermore, delamination occurs over an increasing large surface area so that the amount of energy necessary to effect substantial delamination is even more significant depending on the duration of the applied force. At impact, the kinetic energy (KE) of the threat is transferred to the composite in milliseconds, while the delamination-associated mechanisms act as energy sponges absorbing and dissipating the damage produced by projectile penetration. It is the energy-absorbing feature of polymer composite laminates that, with proper design and fabrication, can result in a new generation of lighter, primary, structural armor materiel.

1.2 SMARTweave Technology. SMARTweave [1] is a novel system designed to efficiently and economically retrieve "state" data from a distributed array of sensors. "State" refers to the parameter, or series of parameters, that one may wish to monitor and track during a series of prescribed or witnessed events. For example, the state of resin flow is a desired parameter in the assessment of the resin-transfer molding (RTM) process; the event is the physical impregnation of the fibrous preform by the polymer resin. Similarly, monitoring the progress of cure in the resin over an array of sensor points is another desirable set of data; the event in this case is the curing of the resin, and the state is defined as the instantaneous degree of cure in the resin.

Generally, the SMARTweave system consists of a sensing grid, a multiplexer designed to rapidly interrogate the grid, an electrical circuit designed to measure an electrical property (e.g., resistance, capacitance, voltage, etc.), and a software-based computer platform to control, record, and display

the flow of sensor data. The sensing grid itself is composed of electrically conductive filaments arranged to produce sensing "gaps" at each of the junctions in the grid. As a conductive material fills these gaps (e.g., resin, moisture, etc.), an electrical measurement is made. If no material is present, the state remains unchanged; if material has arrived, its electrical properties cause a change in state indicating the arrival. This process may be repeated continuously over all the sensing gaps in the grid with the aid of a multiplexer; the result is a discrete representation of material location and material property at any point and at any instant in the grid.

The U.S. Army Research Laboratory (ARL) has developed and applied this patented technology to the RTM process. Monitoring resin flow in the RTM process is critical inasmuch as the flow is responsible for the final mechanical properties of the part. Formation of dry spots due to poor configuration and operation of the RTM process is a common problem. The SMARTweave system has been used successfully to monitor this resin flow and, for the first time, provide an in-situ, real-time assessment of the RTM impregnation process. Most notably, the SMARTweave system was used in the prototype fabrication of the lower hull and crew capsule, two critical components of the Army-sponsored CAV program directed by the U.S. Army Tank-automotive and Armaments Command (TACOM) and contracted to the United Defense Co., San Jose, CA.

The SMARTweave technology has since been demonstrated to possess the potential for other critical applications. For example, as part of an Army Science and Technology Objective (STO), the SMARTweave system was tasked to provide gross-damage information in composite laminates. This gross damage is designed to simulate, for example, the effects of projectile penetration sustained during a conflict. The concept is to ultimately deploy the SMARTweave system as an on-line, real-time, battle-damage detector. Other potential applications include damage detection in marine structures and moisture detection in the charcoal filtration systems of chemical/biological protective suits. These applications could benefit from the SMARTweave's ability to inexpensively and rapidly detect anomalies in the host system environment.

In the present study SMARTweave was investigated as potential in-situ means for determining damage in a polymer composite laminate. Specifically, the research focuses on embedding a sensing

grid composed of commercially available graphite fibers in an array (e.g., 5 × 5) so as to produce 25 unique sensing elements. Each of these elements is uniformly distributed over the surface of the laminate. The goal is to effectively assess the performance of the SMARTweave sensing grid as a means for determining damage induced by ballistic impact.

2. Experimental Procedures

2.1 Specimen Description. Three different specimen types were created for ballistic-damage detection. First, four thin, flat panels were fabricated using a vacuum-assisted RTM process called Seemann Composite Resin Infusion Molding Process (SCRIMP) (see Walsh [1] and Appendix A). A 6 × 6 SMARTweave sensor grid was installed in each of these nominal 0.25-in-thick panels. The second specimen was a 0.5-in-thick, SCRIMP-produced, flat panel containing an 8 × 8 SMARTweave grid. The third specimen was a full-linear-dimensional prototype of the XM194 gun mount shield, except for the wall thickness, which was quarter scale. The XM194 gun mount shield (see Figure 1), from this point on referred to as the "ballistic shield," protects the cooling and recoil mechanisms of the XM297E1 cannon assembly of the 155-mm, advanced, solid propellant, armament system.

2.2 Specimen Fabrication. The first set of specimens (four thin, flat panels) were made using a one-sided aluminum tool and standard, vacuum-bagging technology. The specimens consisted of a 10-ply lay-up of 24-oz, 5 × 4, plain-weave, E-glass fabric. After the fourth ply, six graphite filament "tows," used as SMARTweave sensors, were placed in the horizontal direction and at an equal distance from each other. Following the sixth ply, six additional graphite tows were placed equidistant in the vertical direction. A release-coated nylon fabric (peel ply) was then placed on top of the 10 glass plies. The function of the peel ply is to facilitate removal of the distribution media, which is a nylon cloth material that speeds up the resin infusion process. Next, a single ply of very high-permeability distribution media was laid over the peel ply. This was followed by fitting a helical-cut polyethylene tube alongside one perimeter end and in contact with all the plies. A similar tube was likewise fit to the opposite end of the plies. One of the tubes acted as a "leaky pipe" to

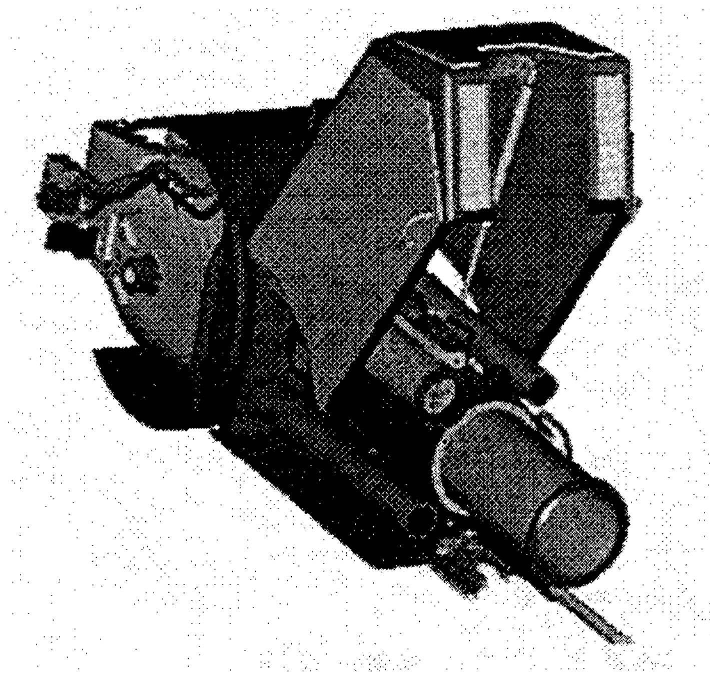


Figure 1. XM194 Gun Mount "Ballistic" Shield.

uniformly introduce resin to the preform; the other acted as the vacuum line. The mold was evacuated and held at full vacuum (29 in of Hg) to provide a pressure gradient for initiating and maintaining resin flow and also to compress the preform. The resin system, Dow Derakane 411-C50, was a vinyl ester resin specially formulated to have a low viscosity for RTM operations. This system also requires a catalyst, Akzo Chemicals Trignox 239A, and a promoter, cobalt napthalate salt (CoNap) solution at 6%. After the resin system was prepared, the feed tube was immersed into the resin and the pinch clamp was released, allowing the vacuum to draw the resin into the preform. The composite panels were cured at room temperature followed by postcuring at 212° F for 2 hr. Appendix B contains the composite processing data sheet for producing the thin panels.

The second specimen, a 23-ply, 0.5-in-thick panel, was fabricated following similar procedures that were used for producing the thin, 10-ply panels (see Appendix B); however, a larger (8 × 8) SMARTweave sensor grid was installed. Eight sensors were placed in the horizontal direction on top of the 11th glass fabric ply and eight sensors were placed vertically after the 13th ply. Figure 2 is a schematic representation of the sensor grid lay-up.

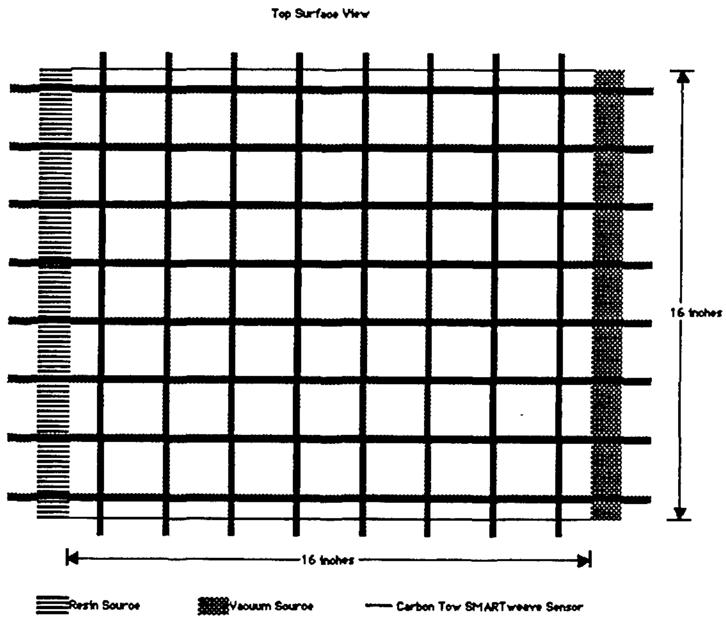


Figure 2. Schematic Representation of the SMARTweave Sensor Grid Lay-Up in the 23-Ply Composite Panel Specimen.

The ballistic shield specimen was manufactured in a composite female tool using the SCRIMP process, and made of 10 plies of 24-oz, 5 × 4, plain-weave, E-glass fabric. SMARTweave sensors (Hercules Magnamite AS4 graphite tows) were placed in the lay-up after the seventh and ninth plies. The graphite tows were laid into the mold in a 16 × 16 grid. The ballistic shield was cured at room temperature and then postcured at 170° F for 3 hr. A photograph of the ballistic shield is shown in Figure 3.

2.3 Ballistic Testing. The four thin panels (specimen nos. 1–4, see Appendix C) and the one thick panel (specimen no. 5, Figure 4) were individually clamped to a test stand 30 ft from the rifle barrel. Specimen no. 1 was tested against the 0.30-cal., 44-grain fragment-simulating projectile (FSP), specimen nos. 2, 3, and 5 were tested against the 0.50-cal., M2 Ball, and specimen no. 4 was tested against the 7.62-mm ball. All of the specimens were tested at 0° obliquity, and each was subjected to no more than three impacts. The impact points were at or near the nodes of the SMARTweave sensor grid, where the full-penetrating projectile damaged the graphite tows, thereby altering electrical continuity. The nodes are pseudo junctions of the orthogonally embedded

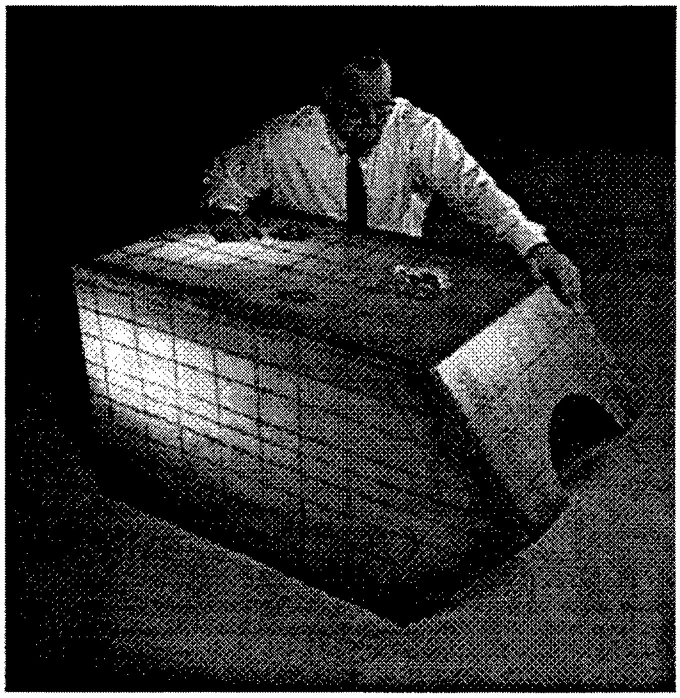
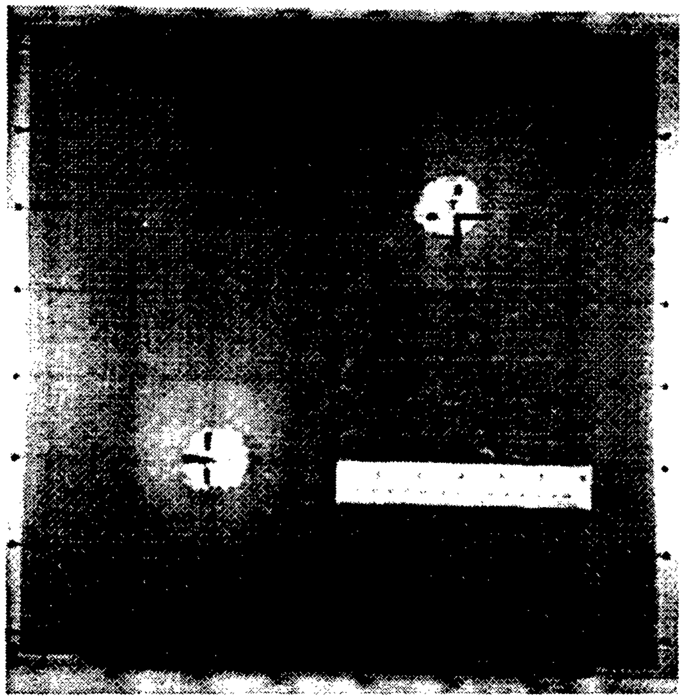


Figure 3. SCRIMP-Manufactured Ballistic Shield Specimen.

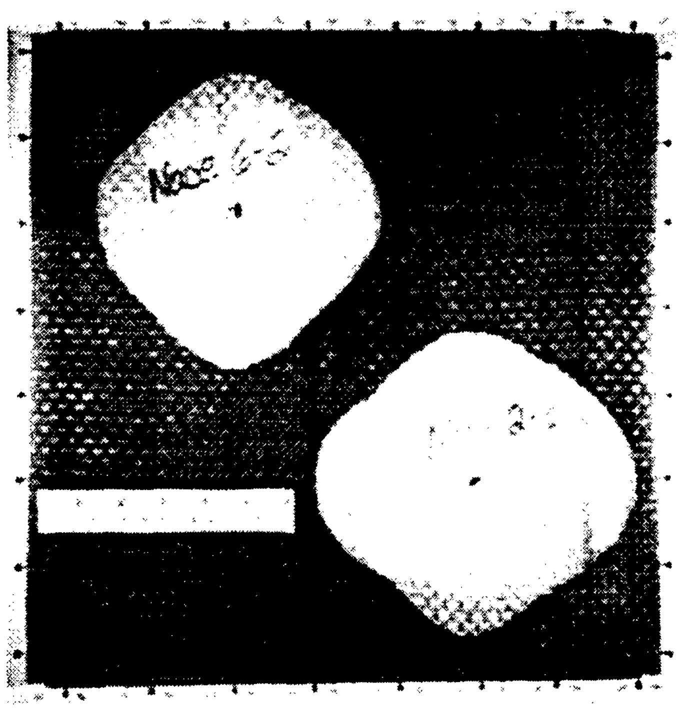
filaments (i.e., they are in close proximity to each other but are not in physical contact). The objective of this test was not to assess the ballistic performance of the fiber/resin composite laminate, but, rather, as stated earlier, to determine if the SMARTweave sensing grid can effectively detect damage induced by ballistic impact.

2.4 Damage Detection. Damage is determined when a statistically significant difference in the electrical resistance is observed between the undamaged and damaged states of the sensors within the laminate. The damage is approximated by considering each of the sensors as having at least four neighboring sensors, both vertically and horizontally. The neighboring sensors not only provide additional spatial sensor information but also serve to corroborate the integrity of a given sensor signal. By multiplexing through all the sensors, one can obtain a sufficient approximation of the damage.

2.5 Ultrasonic Inspection. Specimen no. 5 (0.5-in-thick, 15-in-square, 23-ply composite panel) was nondestructively evaluated before and after ballistic impact by performing an ultrasonic



(a) Impact View.



(b) Back View.

Figure 4. Photographs of the Impacted 23-Ply Composite Panel.

immersion test using the pulse/echo method with a 5-MHz transducer. An automated scanner was utilized to collect A-scans (amplitude vs. time signals) at an interval of 0.0375 in, resulting in a total of 160,000 A-scans. The magnitude of the back surface reflection of each A-scan was measured to determine the relative attenuation of the ultrasonic signal. Attenuation variations are due to signal absorption and scattering within the specimen and can be attributed to inherent characteristics such as density variations, porosity, delaminations, and inclusions. The attenuation of each ultrasonic signal was measured and mapped into a C-scan (a graphical representation of all A-scan attenuation data).

3. Results

3.1 Damage Detection. The electrical resistance data in Figure 5 and Appendix D are the resistance values (in ohms)of each graphite filament sensor (16 total from eight rows and eight columns) measured before and after ballistic impact. The after-ballistic-impact values are shown in parenthesis. The change in resistance is the result of projectile penetration at or near a sensor causing partial separation or complete fracture of the fibrous material. Evaluating all the sensors identifies the location of damage. In the case of the 23-ply composite panel (see Figure 4) the resistance of row nos. 3 and 6 and column nos. 3 and 6 before ballistic impact was approximately 160 Ω. The resistance of these filaments after impact was infinite. Matching up the damaged rows and columns in their respective grid placement allows one to locate the region of ballistic impact. This change in resistance signifies a complete local destruction of the sensor. In thin specimen nos. 1, 3, and 4, the sensors were not damaged at all, which results in the resistance before and after being unaffected. This illustrates that carbon tows, although ideal for process monitoring, are not optimal for ballistic damage detection. However, the resistance change in row no. 4 of thin specimen no. 2 (Figure C-2) went from 167 Ω to 739 Ω, which represents a partial fracture of the sensor and gives promise to the potential of detecting nonterminal damage. To maximize the information regarding damage, a sensor-material substitution could be made. In this study, carbon tows are used as the sensor material; if a sensor material was more sensitive to strain, then smaller changes in strain

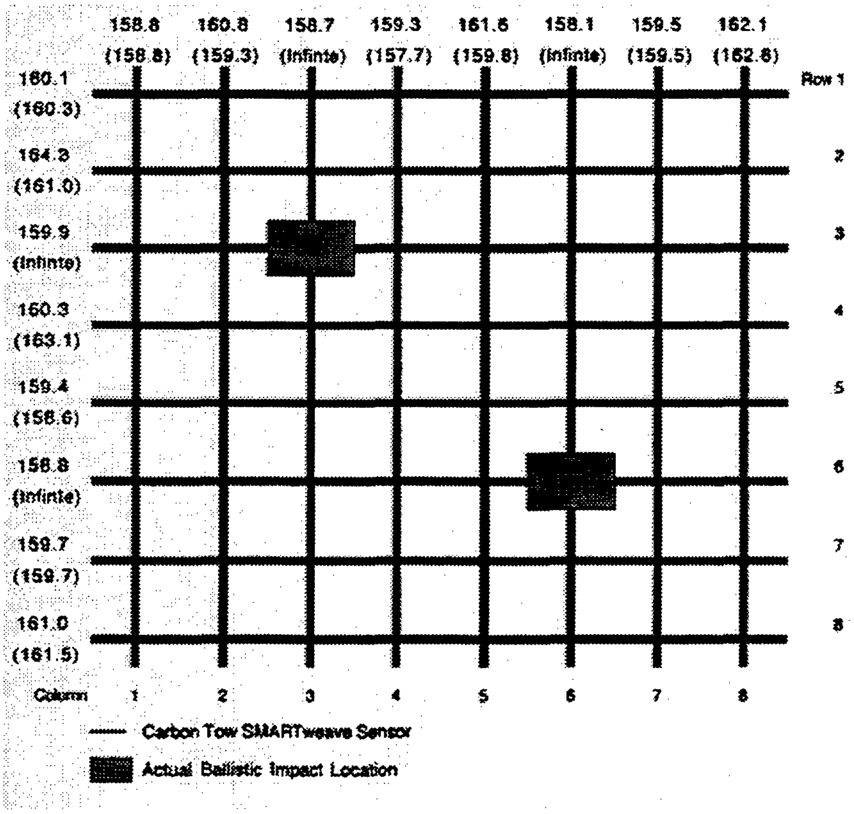
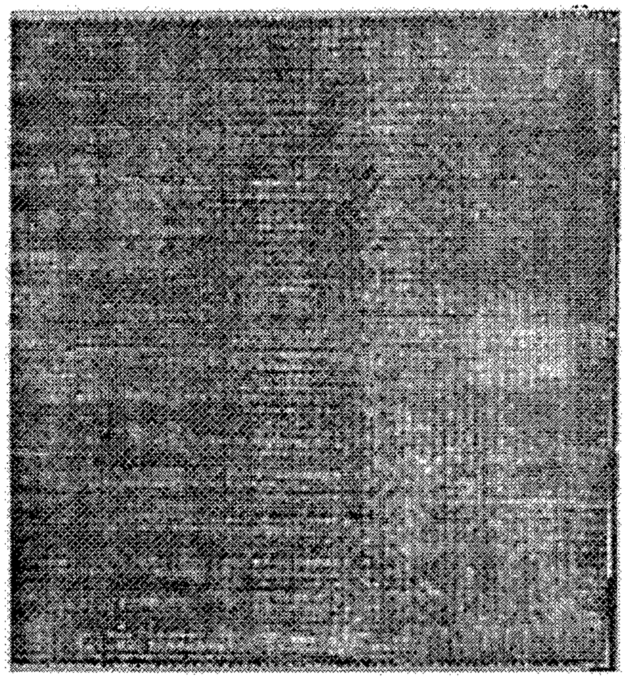


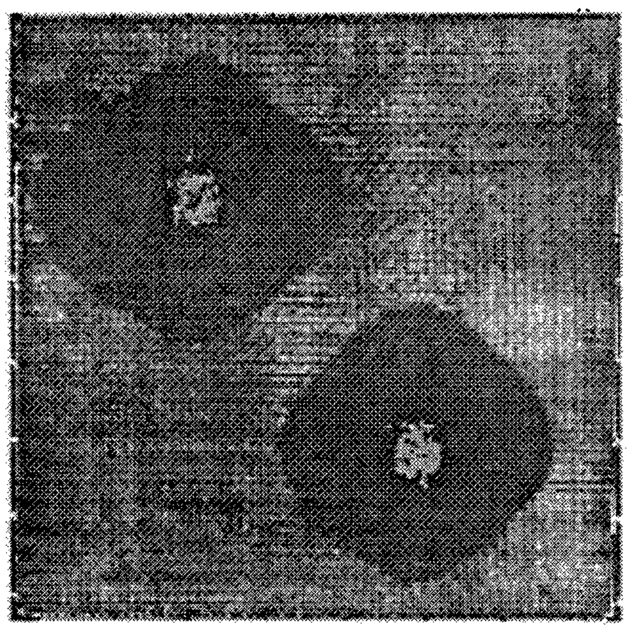
Figure 5. Electrical Resistance Values From the 23-Ply Composite Panel Specimen.

would allow for more significant changes in resistance, which would in turn lead to more detailed damage information.

3.2 Ultrasonic Inspection. Figure 6a presents the attenuation map of the 23-ply panel before ballistic impact. Analysis of the C-scan indicates that the panel was relatively homogeneous with no significant resin-rich areas, dry spots, nor anomalies detected. The attenuation map of the panel after ballistic testing, shown in Figure 6b, depicts the extent of damage (delamination) that occurred as a result of the 0.50-cal. M2 ball impact. The darker (black- and brown-colored) zones represent areas of high attenuation. Due to the large acoustical impedance mismatch between air and the composite material, the ultrasonic signals are almost completely reflected at the delamination interface, resulting in very low-magnitude back reflections. It can be concluded from the analysis of this nondestructive inspection that the detected damage can be attributed to the ballistic test and not to preexisting irregularities within the specimen.



(a) Before Ballistic Impact.



(b) After Ballistic Impact.

Figure 6. Ultrasonic Attenuation Map From the 23-Ply Composite Panel Specimen.

4. Summary

Though preliminary, this study has successfully demonstrated the use of commercial-off-the-shelf (COTS) graphite fibers in a SMARTweave sensing grid as a means for detecting gross ballistic damage. It must also be concluded that the use of a graphite grid for observing resin flow and cure during composite processing is not necessarily optimized for in-situ damage detection in the finished part. Indeed, this study appears to confirm the need for reformulating the SMARTweave sensing grid so that it is properly "tuned" to detect the variations induced by ballistic damage. These modifications might include, but are not limited to, exploring new types of conductive materials, new designs of the sensing elements (i.e., comb configurations to increase local surface area), and alternative electrical property measurements such as capacitance and frequency. However, it should also be noted that any future damage-detection array should preserve the most attractive features of the SMARTweave approach: ease of installation, economic interrogation of large numbers of nodes, and sensor compatibility with the primary structural material.

5. Future Work

Current research efforts are focused on developing and evaluating a variety of alternative sensor materials and configurations specifically formulated for detecting delamination and adhesive-bond failure. While these technologies are designed to provide real-time information on the relative structural integrity of a composite component subject to ballistic impact, increased sensitivity in the grid may also contribute to health monitoring of fielded material subject to less traumatic but, nevertheless, severe environmental or structural loading. The efficient, global interrogation features of the SMARTweave system demonstrated in this study will contribute to the development of future sensing systems that are increasingly viable and cost effective.

6. References

1. Walsh, S. W. "In-Situ Sensor Method and Device." U.S. Patent No. 5,210,499, 11 May 1993.

2. Seemann, W. H. "Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, 20 February 1990.

INTENTIONALLY LEFT BLANK.

Appendix A:

Seemann Composite Resin Infusion Molding Process (SCRIMP)

INTENTIONALLY LEFT BLANK.

The Seemann composite resin infusion molding process (SCRIMP)[1] is a process by which a thermosetting resin is infiltrated into a fibrous preform. The advantages of this process are (1) SCRIMP is a low-cost, repeatable composite process method utilizing only a one-sided tool (mold) and standard vacuum-bagging technology and (2) dependent on the fabric architecture, SCRIMP can yield excellent volume fractions of fibers on the order of 50–55%. Complex three-dimensional (3-D) and trussed structures and thick-section composites (on the order of 6 in thick) can be manufactured. The primary disadvantage of SCRIMP is that only one side of the component has a good (or smooth) surface finish due to the fact that only one-sided tooling is employed. Figure A-1 shows a schematic of SCRIMP.

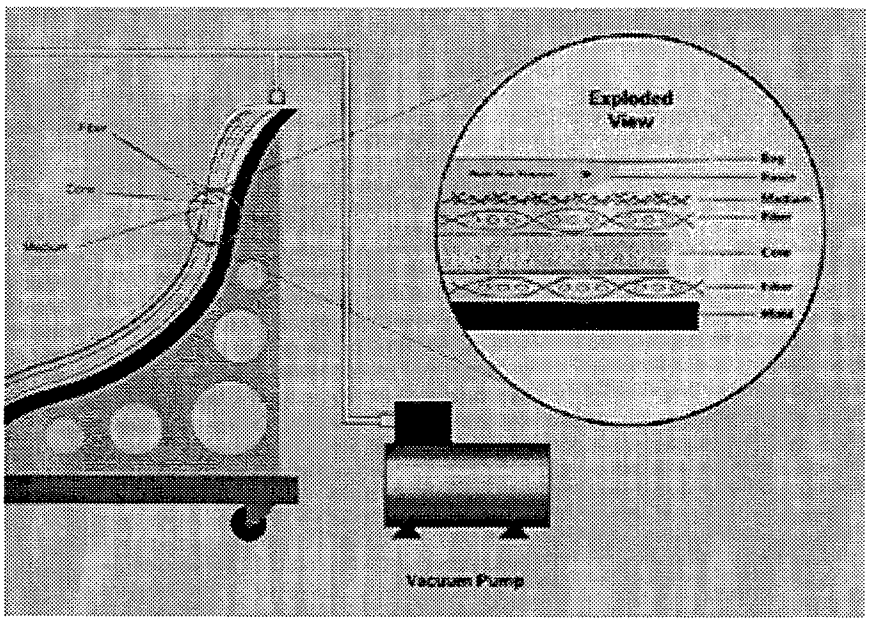


Figure A-1. Schematic of SCRIMP, courtesy of Seemann Composites, Inc.

[1] Seemann, W. H. "Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, 20 February 1990.

INTENTIONALLY LEFT BLANK.

Appendix B:

Composite Processing Data Sheets

INTENTIONALLY LEFT BLANK.

DATE: 10 April 1996

PERSONNEL: Bill Ballata and Dan Snoha

OBJECTIVE: To produce a thick composite panel with SMARTweave sensors that can be ballistically tested to evaluated its ability to detect damage.

LAY-UP SEQUENCE (from top surface to bottom surface):

(1) Vacuum bag
(2) Distribution media
(3) Peel ply
(4) 5 × 4 glass fabric, 9 plies, 17 in × 17 in
(5) SMARTweave sensors, 8 carbon tows, horizontally oriented
(6) 5 × 4 glass fabric, 3 plies, 17 in × 17 in
(7) SMARTweave sensors, 8 carbon tows, vertically oriented
(8) 5 × 4 glass fabric, 9 plies, 17 in × 17 in
(9) 5 × 4 glass fabric, 2 plies, 17 in × 19 in
(10) Tool

RESIN SYSTEM:

Component	Concentration (%)	Mass (g)	Volume (ml)
Total Resin	100.00	2552.15	2416.86
411-C50	97.80	2496.00	2400.00
Trigonox	2.00	51.04	56.71
CoNap	0.20	5.11	5.16
Gel Time: 30 min			

NOTES:

(1) The feeder tube was wrapped in distribution media.
(2) There seemed to be a small point leak where a few bubbles were able to get into the part. This leak occurred at the opposite end of the feeder tube from the inlet point. In the final part, some small voids were noticed along that edge. From this note, it is suggested to use two boundaries of tacky tape in the future.
(3) 3M Super 77 spray adhesive was used along the edges to help hold the preform in place. It was noticed on the final part that the spray adhesive, used extremely sparingly, did have some type of negative effect on the part quality.
(4) The part was postcured at 100° C for 2 hr.
(5) The glass fabric is 5 × 4 E-glass in a plain weave. The sizing on the fabric is unknown but probably a general-use epoxy/polyester sizing. The resin is a vinyl ester from Dow, 411-C50. The volume fraction of the E-glass is between 52% and 54%. The SMARTweave sensors are carbon tows (graphite fiber bundles).

DATE: 02 July 1996

PERSONNEL: Bill Ballata and Clarissa DuBois

OBJECTIVE: To produce a panel with SMARTweave sensors that can be ballistically tested.

LAY-UP SEQUENCE (from top surface to bottom surface):

(1) Vacuum bag
(2) Distribution media
(3) Peel ply
(4) 5 × 4 glass fabric, 4 plies, 30 in × 30 in
(5) SMARTweave sensors, 6 carbon tows, horizontally oriented
(6) 5 × 4 glass fabric, 2 plies, 30 in × 30 in
(7) SMARTweave sensors, 6 carbon tows, vertically oriented
(8) 5 × 4 glass fabric, 3 plies, 30 in × 30 in
(9) 5 × 4 glass fabric, 1 ply, 30 in × 34 in
(10) Tool

RESIN SYSTEM:

Component	Concentration (%)	Mass (g)	Volume (ml)
Total Resin	100.00	2233.13	2154.13
411-C50	97.80	2184.00	2100.00
Trigonox	2.00	44.66	49.62
CoNap	0.20	4.47	4.51
Gel Time: 30 min			

NOTES:

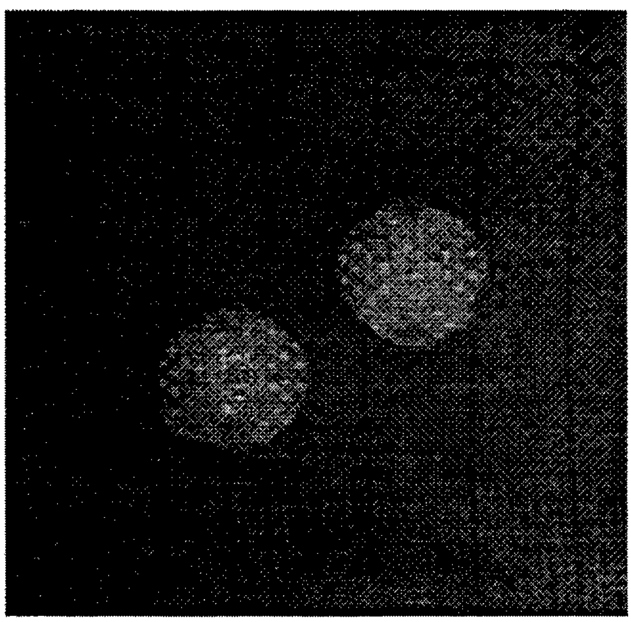
(1) The feeder tube was wrapped in distribution media.
(2) There seemed to be a small point leak where a few bubbles were able to migrate into the part. This leak occurred at the opposite end of the feeder tube from its inlet point. In the cured part, some small voids were noticed along that edge.
(3) 3M Super 77 spray adhesive was used along the edges to help hold the preform in place. It was noticed on the cured part that the spray adhesive, used extremely sparingly, did have some type of negative effect on the part quality.
(4) The part was postcured at 100° C for 2 hr.
(5) The glass fabric is 5 × 4 E-glass in a plain weave. The sizing on the fabric is unknown but probably a general-use epoxy/polyester sizing. The resin is a vinyl ester from Dow, 411-C50. The volume fraction of the E-glass is between 52% and 54%. The SMARTweave sensors are carbon tows (graphite fiber bundles).

Appendix C:

Photographs of the Thin-Panel Specimens After Ballistic Testing

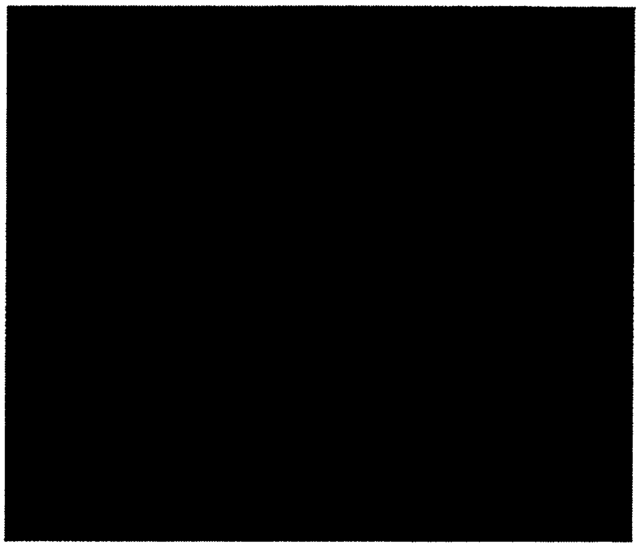
INTENTIONALLY LEFT BLANK.

(a) Impact View.



(b) Back View.

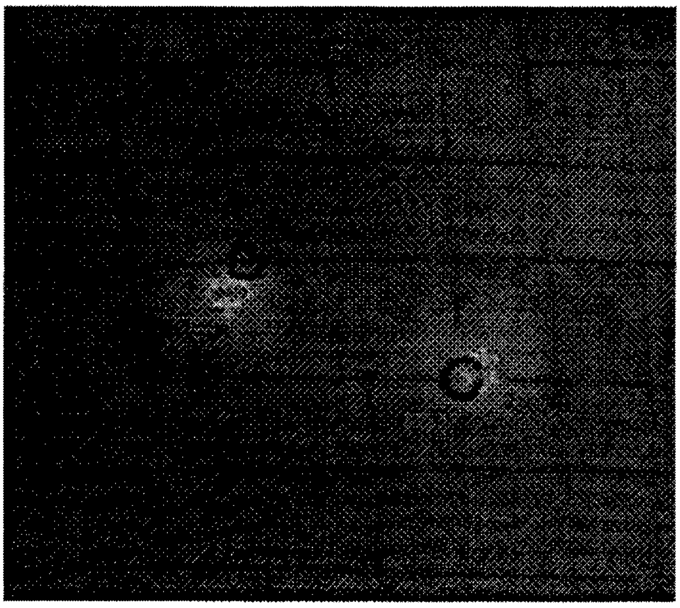
Figure C-1. Thin-Panel Specimens After Ballistic Testing, Panel 1.



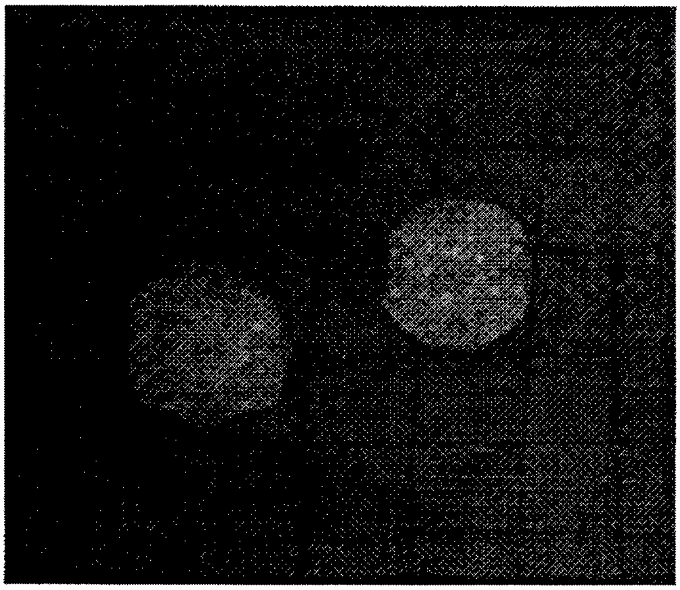
(a) Impact View.

(b) Back View.

Figure C-2. Thin-Panel Specimens After Ballistic Testing, Panel 2.

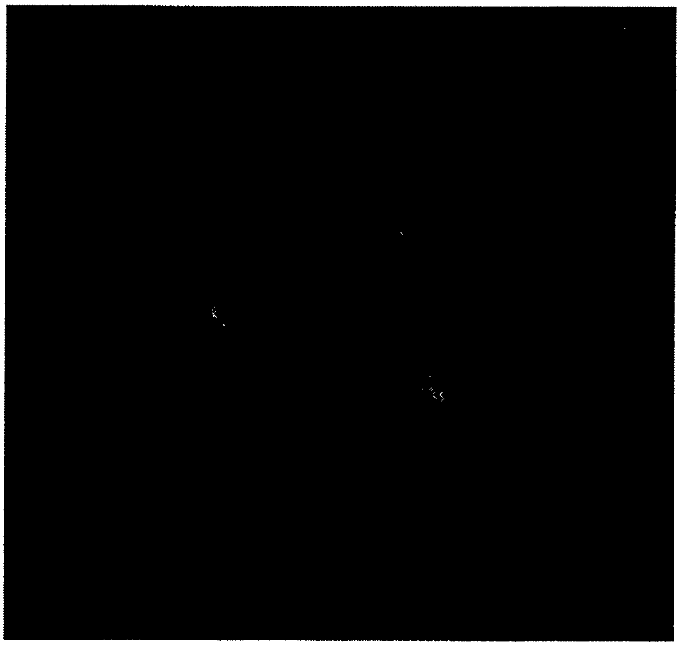


(a) Impact View.

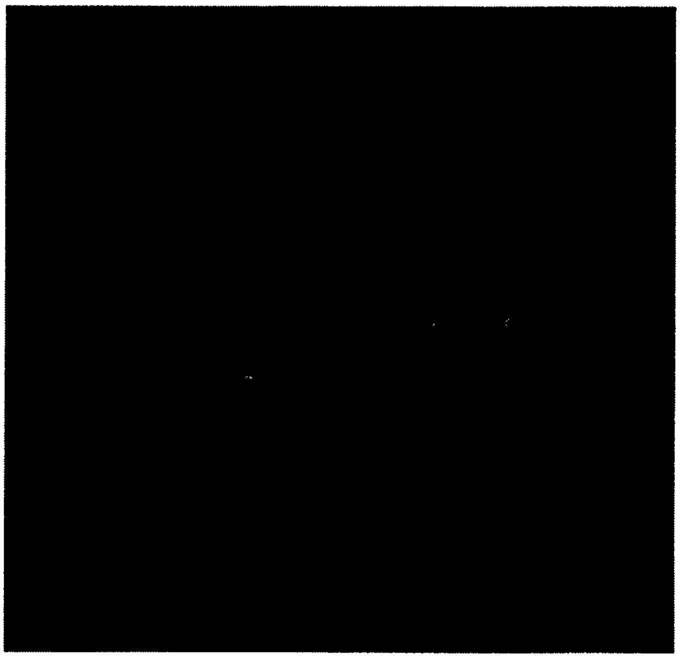


(b) Back View.

Figure C-3. Thin-Panel Specimens After Ballistic Testing, Panel 3.



(a) Impact View.



(b) Back View.

Figure C-4. Thin-Panel Specimens After Ballistic Testing, Panel 4.

Appendix D:

Electrical Resistance Values From the Thin-Panel Specimens

INTENTIONALLY LEFT BLANK.

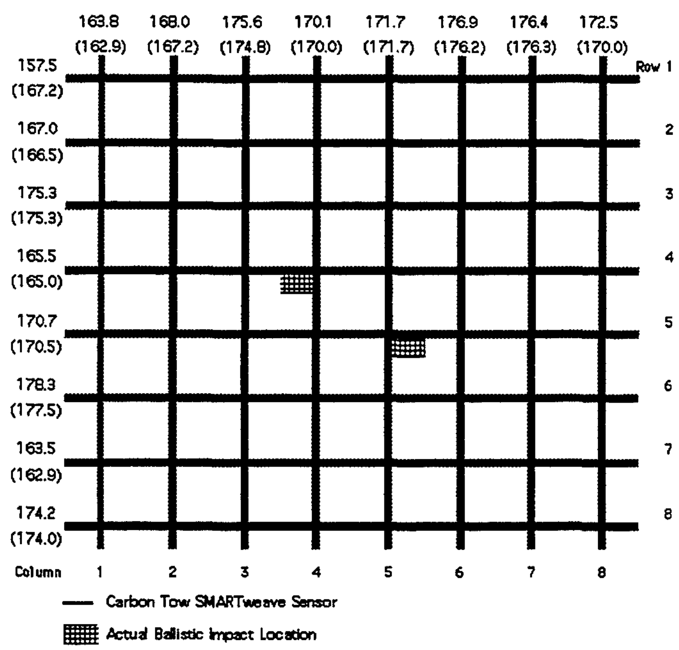


Figure D-1 Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 1 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

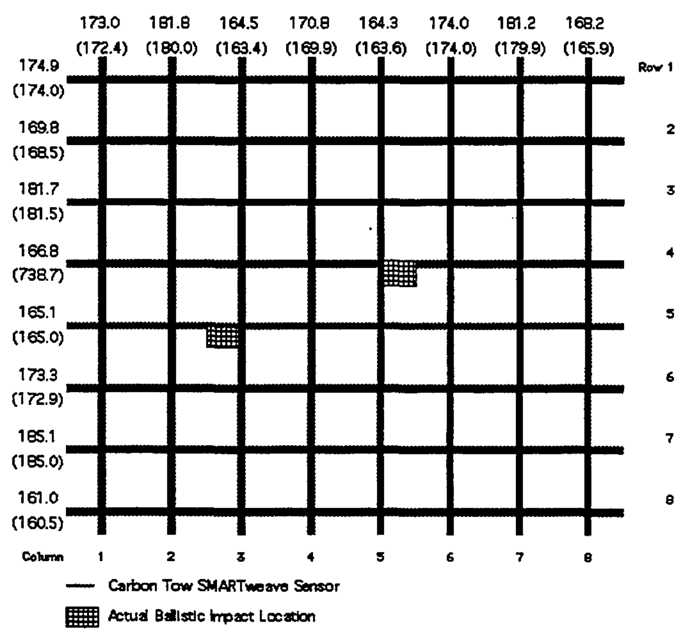


Figure D-2. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 2 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

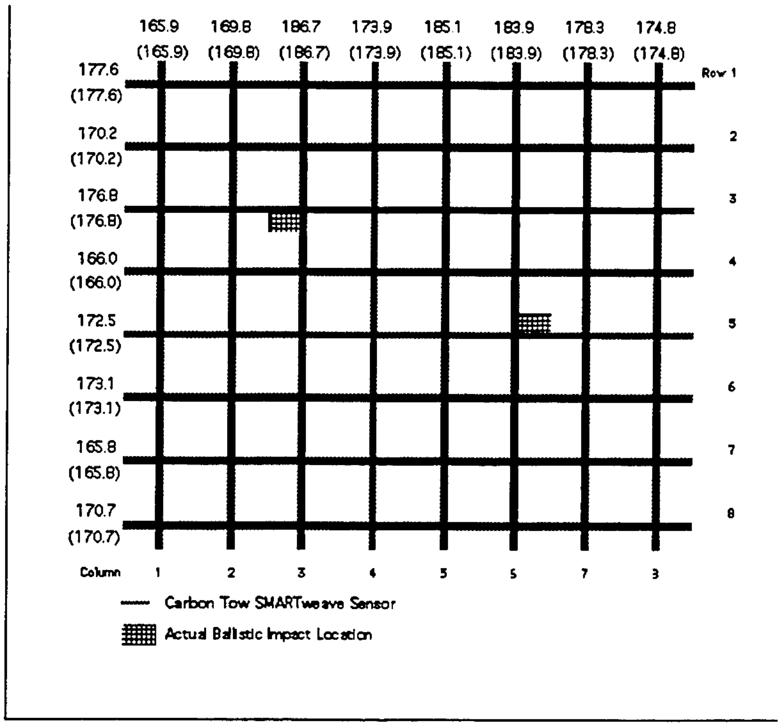


Figure D-3. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 3 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

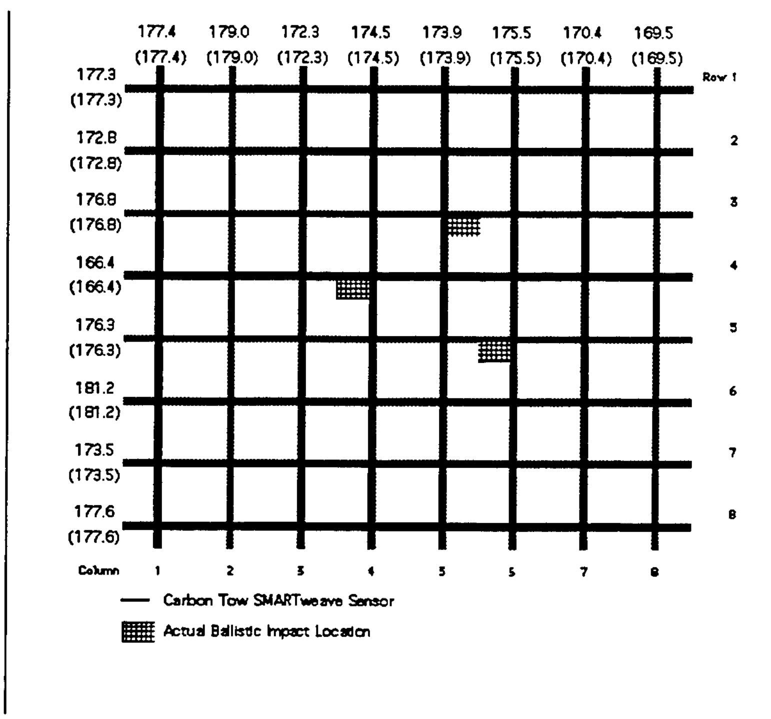


Figure D-4. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 4 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ DENNIS SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	DPTY ASSIST SCY FOR R&T SARD TT F MILTON RM 3EA79 THE PENTAGON WASHINGTON DC 20310-0103
1	OSD OUSD(A&T)/ODDDR&E(R) J LUPO THE PENTAGON WASHINGTON DC 20301-7100
1	CECOM SP & TRRSTRL COMMCTN DIV AMSEL RD ST MC M H SOICHER FT MONMOUTH NJ 07703-5203
1	PRIN DPTY FOR TCHNLGY HQ US ARMY MATCOM AMCDCG T M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	DPTY CG FOR RDE HQ US ARMY MATCOM AMCRD BG BEAUCHAMP 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797

NO. OF COPIES	ORGANIZATION
1	GPS JOINT PROG OFC DIR COL J CLAY 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	ELECTRONIC SYS DIV DIR CECOM RDEC J NIEMELA FT MONMOUTH NJ 07703
3	DARPA L STOTTS J PENNELLA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MDN A MAJ DON ENGEN THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	<u>ABERDEEN PROVING GROUND</u>
4	DIR USARL AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
1	DIRECTOR USARL AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783
1	COMMANDER US ARMY ARDEC AMSTA AR FSE T GORA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR TD R PRICE V LINDNER C SPINELLI PICATINNY ARSENAL NJ 07806-5000
5	US ARMY TACOM AMSTA JSK S GOODMAN J FLORENCE AMSTA TR D B RAJU L HINOJOSA D OSTBERG WARREN MI 48397-5000
5	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC F MCLAUGHLIN PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
5	COMMANDER US ARMY ARDEC AMSTA AR CCH S MUSALLI P CHRISTIAN R CARR M LUCIANO T LOUCEIRO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR E FENNELL PICATINNY ARSENAL NJ 07805-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T/C C PATEL PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA F DIORIO PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK C CHIEFA PICATINNY ARSENAL NJ 07806-5000
8	DIRECTOR BENET LABORATORIES AMSTA AR CCB J KEANE J BATTAGLIA J VASILAKIS G FFIAR V MONTVORI J WRZOCHALSKI R HASENBEIN AMSTA AR CCB R S SOPOK WATERVLIET NJ 12189
1	COMMANDER SMCWV QAE Q B VANINA BLDG 44 WATERVLIET ARSENAL WATERVLIET NY 12189-4050
1	COMMANDER SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET ARSENAL WATERVLIET NY 12189-4050
1	COMMANDER SMCWV QA QS K INSCO WATERVLIET ARSENAL WATERVLIET NY 12189-4050
1	COMMANDER US ARMY ARDEC AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY BELVOIR RD&E CTR STRBE JBC FORT BELVOIR VA 22060-5606
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000
1	US ARMY COLD REGIONS RSRCH & ENGRNG LAB P DUTTA 72 LYME RD HANOVER NH 03755
1	DIRECTOR USARL AMSRL WT L D WOODBURY 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	COMMANDER US ARMY MISSILE CMD AMSMI RD W MCCORKLE AMSMI RD ST P DOYLE AMSMI RD ST CN T VANDIVER REDSTONE ARSENAL AL 35898-5247
2	US ARMY RSRCH OFC A CROWSON J CHANDRA PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
5	PROJECT MANAGER TMAS SFAE GSSC TMA COL PAWLICKI K KIMKER E KOPACZ R ROESER B DORCY PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	PROJECT MANAGER TMAS SFAE GSSC TMA SMD R KOWALSKI PICATINNY ARSENAL NJ 07806-5000
2	PEO FIELD ARTILLERY SYS SFAE FAS PM H GOLDMAN T MCWILLIAMS PICATINNY ARSENAL NJ 07806-5000
2	PROJECT MGR CRUSADER G DELCOCO J SHIELDS PICATINNY ARSENAL NJ 07806-5000
2	NASA LANGLEY RSRCH CTR MS 266 AMSRL VS W ELBER F BARTLETT JR HAMPTON VA 23681-0001
2	COMMANDER DARPA J KELLY B WILCOX 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
6	COMMANDER WRIGHT PATTERSON AIR FORCE BASE WL FIV A MAYER WL MLBM S DONALDSON T BENSON TOLLE C BROWNING J MCCOY F ABRAHAMS 2941 P ST STE 1 DAYTON OH 45433
1	NSW CTR DAHLGREN DIV CODE G06 DAHLGREN VA 22448

NO. OF COPIES	ORGANIZATION
1	NAVAL RSRCH LAB CODE 6383 I WOLOCK WASHINGTON DC 20375-5000
1	OFC OF NAVAL RSRCH MECH DIV CODE 1132SM YAPA RAJAPAKSE ARLINGTON VA 22217
1	NSW CTR CRANE DIV M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
1	DAVID TAYLOR RSRCH CTR SHIP STRUCTURES & PROCTECTION DEPT J CORRADO CODE 1702 BETHESDA MD 20084
2	DAVID TAYLOR RSRCH CTR R ROCKWELL W PHYILLAIER BETHESDA MD 20054-5000
1	DEFENSE NUCLEAR AGENCY INNOVATIVE CONCEPTS DIV DR R ROHR 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
1	DR FRANK SHOUP EXPEDITIONARY WARFARE DIV N85 2000 NAVY PENTAGON WASHINGTON DC 20350-2000
1	OFC OF NAVAL RSRCH D SIEGEL 351 800 N QUINCY ST ARLINGTON VA 22217-5660
1	JOSEPH H FRANCIS NSW CTR CODE G30 DAHLGREN VA 2248

NO. OF COPIES	ORGANIZATION
2	NSW CTR CODE G32 DON WILSON CODE G32 R D COOPER DAHLGREN VA 22448
4	NSW CTR CODE G33 JOHN FRAYSSE ELDRIDGE ROWE TOM DURAN LAURA DE SIMONE DAHLGREN VA 22448
1	COMMANDER NAVAL SEA SYS CMD D LIESE 2531 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160
1	NSW MARY E LACY CODE B02 17320 DAHLGREN RD DAHLGREN VA 22448
1	NSW TECH LIB CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
4	DIRECTOR LAWRENCE LIVERMORE NATL LAB R CHRISTENSEN S DETERESA F MAGNESS M FINGER PO BOX 808 LIVERMORE CA 94550
1	LOS ALAMOS NATL LAB F ADDESSIO MS B216 PO BOX 1633 LOS ALAMOS NM 87545
1	LOS ALAMOS NATL LAB R M DAVIS PO BOX 2008 OAK RIDGE TN 27831-6195

NO. OF COPIES	ORGANIZATION
1	PENN STATE UNIV C BAKIS 227 N HAMMOND UNIVERSITY PARK PA 16802
3	UDLP 4800 EAST RIVER RD P JANKE MS170 T GIOVANETTI MS236 B VAN WYK MS389 MINNEAPOLIS MN 55421-1498
4	DIRECTOR SANDIA NATL LAB APPLIED MECHANICS DEPT DIV 8241 W KAWAHARA K PERANO D DAWSON P NIELAN PO BOX 969 LIVERMORE CA 94550-0096
1	BATTELLE C R HARGREAVES 505 KING AVE COLUMBUS OH 43201-2681
1	PACIFIC NORTHWEST LAB M SMITH PO BOX 999 RICHLAND WA 99352
1	LAWRENCE LIVERMORE NATL LAB M MURPHY PO BOX 808 L282 LIVERMORE CA 94550
1	DREXEL UNIV ALBERT S D WANG 32ND & CHESTNUT ST PHILADELPHIA PA 19104
1	NC STATE UNIV CIVIL ENGRNG DEPT W RASDORF PO BOX 7908 RALEIGH NC 27696-7908

NO. OF COPIES	ORGANIZATION
1	PENN STATE UNIV RICHARD MCNITT 227 HAMMOND BLDG UNIVERSITY PARK PA 16802
1	PENN STATE UNIV RENATA ENGEL 245 HAMMOND BLDG UNIVERSITY PARK PA 16801
1	PURDUE UNIV SCHOOL OF AERO & ASTRO CT SUN W LAFAYETTE IN 47907-1282
1	STANFORD UNIV DEPT OF AERONAUTICS & AEROBALLISTICS DURANT BLDG S TSAI STANFORD CA 94305
1	UCLA MANE DEPT ENGR IV H THOMAS HAHN LOS ANGELES CA 90024-1597
2	UNIV OF DAYTON RSRCH INST RAN Y KIM AJIT K ROY 300 COLLEGE PARK AVE DAYTON OH 45469-0168
1	UNIVERSITY OF DAYTON JAMES M WHITNEY COLLEGE PARK AVE DAYTON OH 45469-0240
2	UNIV OF DE CTR FOR COMPOSITE MATERIALS J GILLESPIE M SANTARE 201 SPENCER LAB NEWARK DE 18716

NO. OF COPIES	ORGANIZATION
1	UNIV OF IL AT URBANA CHAMPAIGN NATL CTR FOR COMPOSITE MATERIALS RSRCH 216 TALBOT LAB J ECONOMY 104 S WRIGHT ST URBANA IL 61801
1	UNIV OF KY LYNN PENN 763 ANDERSON HALL LEXINGTON KY 40506-0046
1	UNIV OF UT DEPT OF MECH & INDUSTRIAL ENGR S SWANSON SALT LAKE CITY UT 84112
3	THE UNIV OF TX AT AUSTIN CTR FOR ELECTROMECHANICS J PRICE A WALLS J KITZMILLER 10100 BURNET RD AUSTIN TX 78758-4497
3	VPI AND STATE UNIV DEPT OF ESM M W HYER K REIFSNIDER R JONES BLACKSBURG VA 24061-0219
1	UNIV OF MD DR ANTHONY J VIZZINI DEPT OF AEROSPACE ENGRNG COLLEGE PARK MD 20742
1	AAI CORP DR T G STASTNY PO BOX 126 HUNT VALLEY MD 21030-0126
1	JOHN HEBERT PO BOX 1072 HUNT VALLEY MD 21030-0126

NO. OF COPIES	ORGANIZATION
1	ARMTEC DEFENSE PRODUCTS STEVE DYER 85 901 AVE 53 PO BOX 848 COACHELLA CA 92236
2	ADVANCED COMP MATERIALS CORP P HOOD J RHODES 1525 S BUNCOMBE RD GREER SC 29651-9208
1	SAIC DAN DAKIN 2200 POWELL ST STE 1090 EMERYVILLE CA 94608
1	SAIC MILES PALMER 2109 AIR PARK RD S E ALBUQUERQUE NM 87106
1	SAIC ROBERT ACEBAL 1225 JOHNSON FERRY RD STE 100 MARIETTA GA 30068
1	SAIC DR GEORGE CHRYSSOMALLIS 3800 W 80TH STREET STE 1090 BLOOMINGTON MN 55431
4	ALLIANT TECHSYSTEMS INC C CANDLAND R BECKER L LEE R LONG D KAMDAR G KASSUELKE 600 2ND ST NE HOPKINS MN 55343-8367
1	AMOCO PERFORMANCE PRODUCTS INC M MICHNO JR 4500 MCGINNIS FERRY RD ALPHARETTA GA 30202-3944

NO. OF COPIES	ORGANIZATION
1	APPLIED COMPOSITES W GRISCH 333 NORTH SIXTH ST ST CHARLES IL 60174
1	BRUNSWICK DEFENSE T HARRIS STE 410 1745 JEFFERSON DAVIS HWY ARLINGTON VA 22202
1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078
1	CUSTOM ANALYTICAL ENGR SYS INC A ALEXANDER 13000 TENSOR LANE NE FLINTSTONE MD 21530
1	NOESIS INC ALLEN BOUTZ 1110 N GLEBE RD STE 250 ARLINGTON VA 22201-4795
1	ARROW TECH ASSO 1233 SHELBURNE RD STE D 8 SOUTH BURLINGTON VT 05403-7700
1	NSWC R HUBBARD G33 C DAHLGREN DIV DAHLGREN VA 22448-5000
5	GEN CORP AEROJET D PILLASCH T COULTER C FLYNN D RUBAREZUL M GREINER 1100 WEST HOLLYVALE ST AZUSA CA 91702-0296

NO. OF COPIES	ORGANIZATION
7	CIVIL ENGR RSRCH FOUNDATION H BERNSTEIN PRESIDENT C MAGNELL K ALMOND R BELLE M WILLETT E DELO B MATTES 1015 15TH ST NW STE 600 WASHINGTON DC 20005
1	NIST STRCTRE & MCHNCS GROUP POLYMER DIV POLYMERS RM A209 GREGORY MCKENNA GAITHERSBURG MD 20899
1	DUPONT COMPANY COMPOSITES ARAMID FIBERS S BORLESKE DVLPMNT MGR CHESNUT RUN PLAZA PO BOX 80702 WILMINGTON DE 19880-0702
1	GENERAL DYNAMICS LAND SYSTEMS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090
3	HERCULES INC R BOE F POLICELLI J POESCH PO BOX 98 MAGNA UT 84044
3	HERCULES INC G KUEBELER J VERMEYCHUK B MANDERVILLE JR HERCULES PLZ WILMINGTON DE 19894
1	HEXCEL M SHELENDICH 11555 DUBLIN BLVD PO BOX 2312 DUBLIN CA 94568-0705

NO. OF COPIES	ORGANIZATION
1	IAP RESEARCH INC A CHALLITA 2763 CULVER AVE DAYTON OH 45429
5	INSTITUTE FOR ADVANCED TECH T KIEHNE H FAIR P SULLIVAN W REINECKE I MCNAB 4030 2 W BRAKER LN AUSTIN TX 78759
1	INTEGRATED COMPOSITE TECH H PERKINSON JR PO BOX 397 YORK NEW SALEM PA 17371-0397
1	INTERFEROMETRICS INC R LARRIVA VICE PRESIDENT 8150 LEESBURG PIKE VIENNA VA 22100
1	AEROSPACE RES & DEV (ASRDD) CORP D ELDER PO BOX 49472 COLORADO SPRINGS CO 80949-9472
1	PM ADVANCED CONCEPTS LORAL VOUGHT SYSTEMS J TAYLOR PO BOX 650003 MS WT 21 DALLAS TX 76265-0003
2	LORAL VOUGHT SYSTEMS G JACKSON K COOK 1701 W MARSHALL DR GRAND PRAIRIE TX 75051
1	BRIGS CO JOE BACKOFEN 2668 PETERBOROUGH ST HERDON VA 22071-2443

NO. OF COPIES	ORGANIZATION
1	SOUTHWEST RSRCH INSTITUTE JACK RIEGEL ENGRG & MTRL SCIENCES DIV 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
1	ZERNOW TECHNICAL SERVICES LOUIS ZERNOW 425 W BONITA AVE SUITE 208 SAN DIMAS CA 91773
1	ROBERT EICHELBERGER CONSULTANT 409 W CATHERINE ST BEL AIR MD 21014-3613
1	DYNA EAST CORPORATION PEI CHI CHOU 3201 ARCH ST PHILADELPHIA PA 19104-2711
2	MARTIN MARIETTA CORP P DEWAR L SPONAR 230 EAST GODDARD BLVD KING OF PRUSSIA PA 19406
2	OLIN CORPORATION FLINCHBAUGH DIV E STEINER B STEWART PO BOX 127 RED LION PA 17356
1	OLIN CORPORATION L WHITMORE 10101 9TH ST NORTH ST PETERBURG FL 33702
1	RENNSAELER PLYTCHNC INST R B PIPES PRESIDENT OFC PITTSBURGH BLDG TROY NY 12180-3590
1	SPARTA INC J GLATZ 9455 TOWNE CTR DRIVE SAN DIEGO CA 92121-1964

NO. OF COPIES	ORGANIZATION
2	UNITED DEFENSE LP P PARA G THOMAS 1107 COLEMAN AVE BOX 367 SAN JOSE CA 95103
1	MARINE CORPS SYSTEMS CMD PROGRAM MGR GROUND WPNS COL RICK OWEN 2083 BARNETT AVE SUITE 315 QUANTICO VA 22134-5000
1	OFFICE OF NAVAL RES J KELLY 800 NORTH QUINCEY ST ARLINGTON VA 22217-5000
2	NSWC CARDEROCK DIV R CRANE CODE 2802 C WILLIAMS CODE 6553 3A LEGGETT CIR ANNAPOLIS MD 21402
5	SIKORSKY H BUTTS T CARSTENSAN B KAY S GARBO J ADELMANN 6900 MAIN ST PO BOX 9729 STRATFORD CT 06601-1381
1	D ADAMS U WYOMING PO BOX 3295 LARAMIE WY 82071
1	MICHIGAN ST UNIVERSITY R AVERILL 3515 EB MSM DEPT EAST LANSING MI 48824-1226
1	AMOCO POLYMERS J BANISAUKAS 4500 MCGINNIS FERRY RD ALPHARETTA GA 30005

NO. OF COPIES	ORGANIZATION
1	HEXCEL T BITZER 11711 DUBLIN BLVD DUBLIN CA 94568
1	BOEING R BOHLMANN PO BOX 516 MC 5021322 ST LOUIS MO 63166-0516
1	NAVSEA OJRI G CAMPONESCHI 2351 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160
1	LOCKHEED MARTIN R FIELDS 1195 IRWIN CT WINTER SPRINGS FL 32708
1	USAF WL/MLS OL A HAKIM 5225 BAILEY LOOP 243E MCCLELLAN AFB CA 55552
1	PRATT & WHITNEY D HAMBRICK 400 MAIN ST MS 114 37 EAST HARTFORD CT 06108
1	DOUGLAS PRODUCTS DIV BOEING L J HART-SMITH 3855 LAKEWOOD BLVD D800-0019 LONG BEACH CA 90846-0001
1	MIT P LAGACE 77 MASS AVE CAMBRIDGE MA 01887
1	NASA LANGLEY J MASTERS MS 389 HAMPTON VA 23662-5225

NO. OF COPIES	ORGANIZATION
1	CYTEC M LIN 1440 N KRAEMER BLVD ANAHEIM CA 92806
2	BOEING ROTORCRAFT P MINGURT P HANDEL 800 B PUTNAM BLVD WALLINGFORD PA 19086
2	FAA TECH CENTER D OPLINGER AAR 431 P SHYPRYKEVICH AAR 431 ATLANTIC CITY INTL AIRPORT NJ 08405
1	NASA LANGLEY RC CC POE MS 188E NEWPORT NEWS VA 23608
1	LOCKHEED MARTIN S REEVE 8650 COBB DR D/73-62 MZ 0648 MARIETTA GA 30063-0648
1	WL/MLBC E SHINN 2941 PST STE 1 WRIGHT PATTERSON AFB OH 45433-7750
2	IIT RESEARCH CENTER D ROSE 201 MILL ST ROME NY 13440-6916
1	MATERIALS SCIENCES CORP BW ROSEN 500 OFFICE CENTER DR STE 250 FT WASHINGTON PA 19034
1	DOW UT S TIDRICK 15 STERLING DR WALLINGFORD CT 06492

NO. OF COPIES	ORGANIZATION
3	TUSKEGEE UNIVERSITY MATERIALS RSRCH LAB SCHOOL OF ENGR & ARCH S JEELANI H MAHFUZ U VAIDYA TUSKEGEE AL 36088
4	NIST R PARNAS J DUNKERS M VANLANDINGHAM D HUNSTON POLYMERS DIVISION GAITHERSBURG MD 20899
2	NORTHROP GRUMMAN ENVIRONMENTAL PROGRAMS R OSTERMAN 8900 E WASHINGTON BLVD PICO RIVERA CA 90660
1	OAK RIDGE NATL LAB A WERESZCZAK BLDG 4515 MS 6069 PO BOX 2008 OAKRIDGE TN 37831-6064
1	COMMANDER US ARMY ARDEC T SACHAR INDUSTRIAL ECOLOGY CTR BLDG 172 PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ATCOM AVIATION APPLIED TECH DIR J SCHUCK FORT EUSTIS VA 23604-1104
1	COMMANDER US ARMY ARDEC AMSTA AR SRE D YEE PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
7	COMMANDER US ARMY ARDEC AMSTA AR CCH B B KONRAD E RIVERA G EUSTICE S PATEL G WAGNECZ R SAYER F CHANG BLDG 65 PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO BLDG 354 M829E3 IPT PICATINNY ARSENAL NJ 07806-5000
	ABERDEEN PROVING GROUND
75	DIR USARL AMSRL CI C NIETUBICZ 394 AMSRL CI C W STUREK 1121 AMSRL CI CB R KASTE 394 AMSRL CI S A MARK 309 AMSRL SL B AMSRL SL BA AMSRL SL BE D BELY 328 AMSRL WM B A HORST 390A E SCHMIDT 390A AMSRL WM BE G KELLER 390 C LEVERITT 390 D KOOKER 390A AMSRL WM BC P PLOSTINS 390 D LYON 390 J NEWILL 390 S WILKERSON 390 AMSRL WM BD R FIFER 390 B FORCH 390A R PESCE-RODRIGUEZ 390 B RICE 390A

NO. OF COPIES	ORGANIZATION
	AMSRL WM D VIECHNICK 4600 G HAGNAUER 4600 J MCCAULEY 4600 AMSRL WM MA R SHUFORD 4600 S MCKNIGHT 4600 AMSRL WM MB B BURNS 4600 W DRYSDALE 4600 J BENDER 4600 T BLANAS 4600 T BOGETTI 4600 R BOSSOLI 120 L BURTON 4600 J CONNORS 4600 S CORNELISON 120 P DEHMER 4600 R BOOLEY 4600 B FINK 4600 G GAZONAS 4600 S GHIORSE 4600 D GRANVILLE 4600 D HOPKINS 4600 C HOPPEL 4600 D HENRY 4600 R KASTE 4600 R KLINGER 4600 M LEADORE 4600 R LIEB 4600 E RIGAS 4600 D SPAGNUOLO 4600 W SPURGEON 4600 J TZENG 4600 AMSRL WM MB ALC A ABRAHAMIAN M BERMAN A FRYDMAN T LI W MCINTOSH E SZYMANSKI AMSRL WM MC T HYNES 4600 AMSRL WM MD W ROY 4600 AMSRL WM ME R ADLER 4600 AMSRL WM T W MORRISON 309 AMSRL WM TA W GILLICH 393 W BRUCHEY 393 T HAVEL 393 AMSRL WM TC R COATES 309 W DE ROSSET 309 AMSRL WM TD T CHOU 4600 D DIETRICH 309 A DAS GUPTA 309 AMSRL WM TE J POWELL 120 AMSRL WM BA F BRANDON 120 W D AMICO 120 AMSRL WM BB J BORNSTEIN 120 AMSRL WM BC A ZIELINSKI 390 AMSRL WM BF J LACETERA 120

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1998	Final, Jun 96 - Nov 97

4. TITLE AND SUBTITLE

SMARTweave Sensors for Assessing Ballistic Damage: a Feasibility Study

5. FUNDING NUMBERS

COMPO2

6. AUTHOR(S)

Daniel J. Snoha, William O. Ballata, and Shawn M. Walsh

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-1674

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

SMARTweave technology, developed and patented by the U.S. Army Research Laboratory (ARL), has been applied to monitor resin flow and cure progress in composite laminate processing. It has since demonstrated the capacity of being a viable sensing mechanism in other critical applications. In this feasibility study, for example, SMARTweave sensors have successfully shown the potential for detecting ballistic-impact-induced damage in a composite laminate. A sensing grid of electrically conductive graphite fibers was embedded in the composite specimens during lay-up of the glass-fabric preforms. The results of electrical resistance measurements preformed before and after ballistic impact, with the difference indicating the detection of induced damage (delamination), are presented herein. For purposes of qualitative comparison, a traditional, ultrasonic, nondestructive, evaluation technique was also used to capture the effects of the induced damage. This research was conducted during the period that the Materials Division was in transition from ARL, Watertown, MA, to the Rodman Materials Research Laboratory, Aberdeen Proving Ground (APG), MD.

14. SUBJECT TERMS

SMARTweave, damage detection, health monitoring

15. NUMBER OF PAGES

34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1674 (Snoha) ____________ Date of Report May 1998 ________

2. Date Report Received ______________________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______________________________

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)